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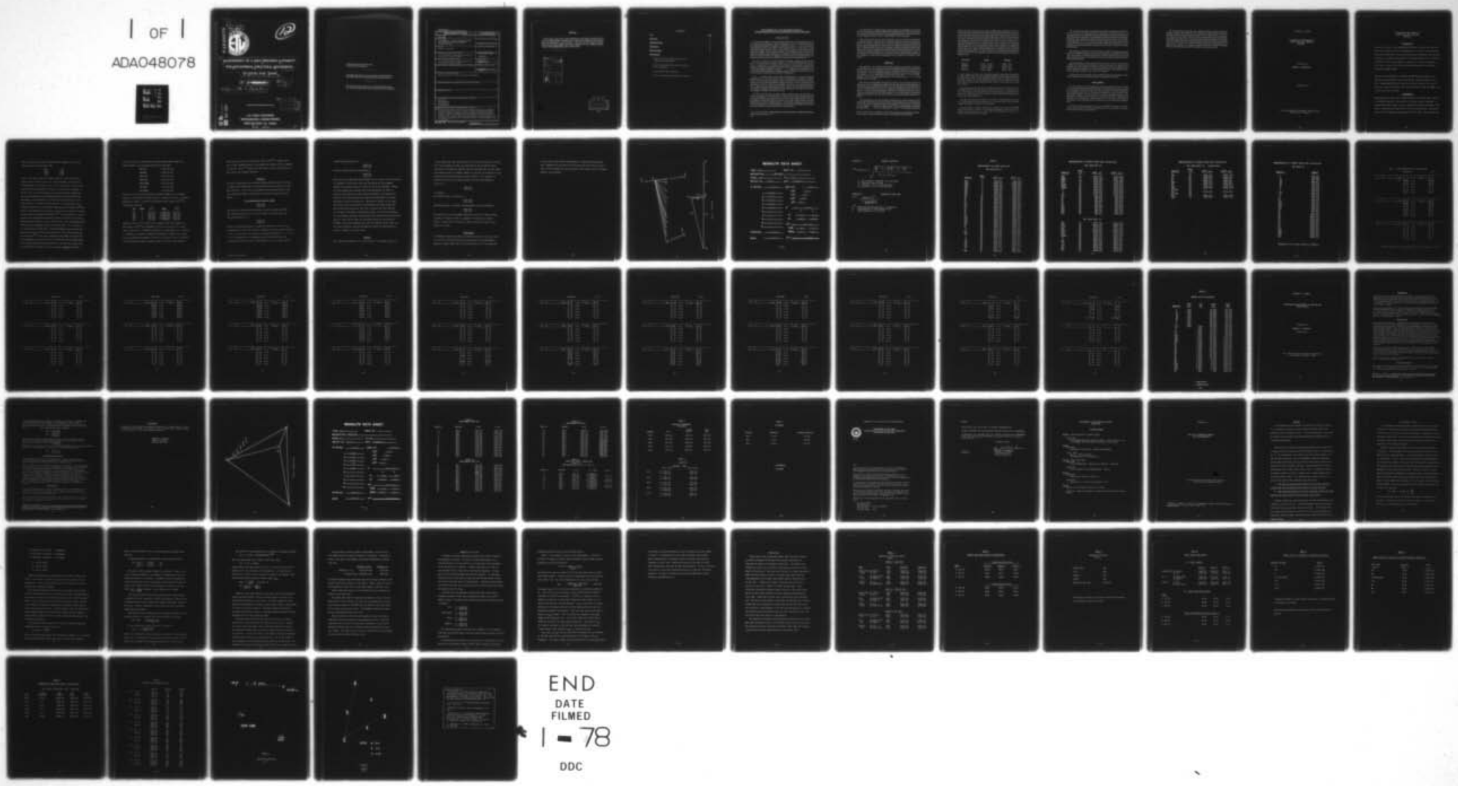

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DEVELOPMENT OF A HIGH PRECISION CAPABILITY FOR MONITORING STRUCTURAL MOVEMENTS OF LOCKS AND DAMS,

11 SEP [redacted] 77

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10 Kenneth D. /Robertson

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A program of periodic inspection and continuing evaluation is required to insure the safety of many civil works structures. This report documents a Corps of Engineers program to develop a capability within the various Engineer districts for making very high precision survey measurements of structures. The program consisted of measurements of several structures and of training programs for survey personnel. Results of the measurements are included.		

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PREFACE

This report is a summary of work performed by the Research Institute, ETL on work unit 16R67RI0001, "Development of a High Precision Capability for Monitoring Structural Movements of Locks and Dams." This work has also resulted in the publication of ETL Report 0048, "The Use and Calibration of Distance Measuring Equipment for Precise Mensuration of Dams," March 1976.

A023 759

CONTENTS

DEVELOPMENT OF A HIGH PRECISION CAPABILITY FOR MONITORING STRUCTURAL MOVEMENTS OF LOCKS AND DAMS

INTRODUCTION

The structural integrity of major Civil Works projects is of continuing concern to the U.S. Army Corps of Engineers. Engineer Regulation 1110-2-100, "Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures," states as its objective: "Civil Works structures whose failure would endanger the lives of the public or cause substantial property damage will be continuously evaluated to insure their structural safety and stability, and operational adequacy. Such evaluations, based upon periodic inspections supported when appropriate by programs of instrumentation, will be conducted to detect conditions of significant structural distress or operational inadequacy and to provide a basis for timely initiation of restorative and remedial measures." [1]

One way of helping to meet this objective is through a program of high precision survey. The instrumentation program required by ER 1110-2-100 includes the measurement of "Displacements or changes in the position of each individual monolith with respect to the dam axis, usually at the roadway level" and "Deflection and tilting of one or more of the higher monoliths in the dam . . . ." [2] Programs of instrumentation also include high order triangulation or alignment surveys, measurements of tilting and external deformation, and horizontal movements of embankments.

Thus, an important part of the periodic inspection and the continuing evaluation program consists of very high precision survey. Traditionally, or perhaps by necessity, precise survey has consisted of alignment with a T-3 type of instrument and a micrometer target and of high order triangulation. Alignment, however, related movements to the abutments of the dam, which may themselves have moved, was generally performed only at night because of atmospheric turbulence, and in a practical sense was limited to the roadway of straight dams. In addition, both triangulation and alignment are victims of atmospheric refraction, which limits accuracy.

In recent years, the advent of lasers, infrared emitting diodes, and solid state electronics has permitted the development of compact, direct reading distance measuring equipment (DME) with potential accuracies of one part per million or greater. Surveyors have eagerly accepted these devices for routine survey work, usually attaining accuracies ranging up to one part in 25,000. However, a vast difference exists between the normal type of boundary survey or photogrammetric control survey using DME and the ultraprecise survey required to monitor movements in locks and dams.

[1] U.S. Army Corps of Engineers, **"Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures,"** ER 1110-2-100, 26 February 1973

[2] Ibid.

ETL has had, for a number of years, an active program in using DME for very precise survey and has developed special techniques for minimizing the error sources, which pose the ultimate limit to their accuracy. It seems a natural progression to adapt DME and the special techniques developed by ETL to the problems of dam mensuration.

Thus, the objectives for the work reported here were stated in the Civil Works Research Work Unit as: "The work to be performed under this work unit is designed to provide the Corps of Engineers with an in-house capability for making highly precise measurements of displacements or deflections in Civil Works structures such as dams and locks. A further objective of the work is to suggest techniques and instrumentation which will be cost effective, if possible less expensive than the methods presently used. Another objective is to provide measurements of several structures to demonstrate the accuracy of the techniques. The final objective of the work is to train Corps of Engineer personnel in the techniques so that future measurements may be carried out by District survey parties."

APPROACH

The approach to this work has been through a program of several phases. Four dams were selected as test and training sites based on geographic location and a diversification of dam types. Each dam eventually served as a training site for district personnel, but it first served as a test site for adaptation of DME techniques, under a variety of conditions, to the problems of dam mensuration. The sites chosen were Oahe Dam, Pierre, S. Dak., Hannibal Locks and Dam, New Martinsville, W. Va., Green Peter Dam, Foster, Ore., and Keystone Dam, Tulsa, Okla.

Pedestals for mounting DME were located at each site, and an initial set of measurements were made of a number of markers on the dam. The purpose of this original set of measurements was to familiarize the district with the operating techniques developed for use in dam mensuration, to obtain a set of data for comparison at a later date, and to provide a variety of measuring situations. This first set of measurements at each of the four dams was obtained with a Geodolite model 3G, an extremely precise, but expensive instrument. Reports of the work were furnished to two of the districts (Appendixes A and B).

The second phase of the work consisted of preparation of a short manual on precise mensuration that could serve as a text for the four survey classes and as a manual for later use by class members in initiating their own programs of precise survey. The manual has been published separately as a report entitled "The Use and Calibration of Distance Measuring Equipment for Precise Mensuration of Dams." [3] The manual contains two

[3]Kenneth D. Robertson, *The Use and Calibration of Distance Measuring Equipment for Precise Mensuration of Dams*, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-0048, March 1976, AD-A023 759.

sections. The first concerns the error sources in DME, proper calibration of reflectors, and refractive index measurements and corrections. This section is also of value to surveyors using their instruments for boundary survey and other lower order work. The second section of the manual covers specific application of DME to dam mensuration and covers such subjects as proper geometry, data reduction, reference lines, and special atmospheric considerations. The manual closes with a complete examination of a dam from beginning to end in cookbook fashion. At the same time the manual was being written, tests were being performed to determine the suitability of commercially available DME for use in the mensuration program. Two instruments, the Tellurometer MA-100 and the Hewlett Packard 3800, had been evaluated as a part of another program and found suitable. Two other instruments, the Keuffel and Esser Ranger IV and the AGA model 76, were evaluated as a part of the current program and also found suitable for use.

Instrument	Range	Precision
MA 100	1 mile 1.5 Km	0.006' 2mm
HP 3800	1½ miles 2.5 Km	0.010' 3mm
AGA 76	3 miles 5.0 Km	0.015' 5mm
Ranger IV	6 miles 10 Km	0.015' 5mm

These results show that, with commercially available instruments, precisions in the range of 0.01 to 0.02 feet can be obtained. Market conditions change rapidly, and the instrument used for a specific application would have to be evaluated and selected from those currently being sold. For example, AGA 76 has been replaced by a later version and is no longer sold, and there is now a Ranger V that has longer range but lesser precision.

The final phase of the work was to schedule and hold the four classes in precise mensuration at or near the dam sites. In January 1976, a letter was sent from OCE to each of the Engineer Divisions outlining the course and requesting nominations. In addition, the information was made available to the U.S. Bureau of Reclamation and the Tennessee Valley Authority.

As replies were received in response to the letter, an acknowledgment was first sent to each individual and then followed 4 to 6 weeks before the course began with complete information. Appendix C is a typical letter.

All four courses were similar. The first day consisted of a review of how DME works. This included a catalog of error sources and techniques for detecting and reducing them. The importance of proper reflector calibration was stressed, and a method of field calibration was explained.

The second day was spent on atmospheric corrections and special ratio techniques for use on dams. For measurements with a high degree of absolute accuracy, it is essential to measure air temperature and pressure along the line. The proper equipment and techniques for doing this were demonstrated, and their limitations were discussed. Fortunately, dam mensuration requires precision rather than accuracy, that is differential movements in X, Y are desired rather than absolute positions. This precision in turn allows the use of ratios or reference lines, which not only avoid most of the problems of measuring atmospheric properties but also provide a quicker and simpler field technique.

The third day was spent in the field at the dam where two different instruments were made available for class use. In the morning of that day, two groups were formed with the first group calibrating their distance measuring equipment and the second group measuring the dam. In the afternoon, the groups exchanged tasks and the morning's work was repeated.

On the fourth day, the data from the field exercise were reduced. The instrument constants were determined and positions of points on the dam were calculated. The positions were then compared with positions determined from the original measurements made with Geodolite. Even with numerous operators using unfamiliar equipment, comparative results of .01 to .02 feet were obtained.

The final day was set aside for review, individual questions, and graduation. Certificates of attendance were awarded to all who were present for the courses.

CONCLUSIONS

For the most part, the four courses have been enthusiastically received. In many cases, a better understanding of DME made the week worthwhile, although there might be no immediate application to dams. For others, adoption of the entire program has been undertaken, and several of the districts, including the St. Louis, Omaha, Tulsa, and Portland Districts, are now making measurements with DME using the special trilateration techniques. Other districts, such as Nashville, Little Rock, Vicksburg, and Savannah, are contemplating or planning this type of measurement. The Bureau of Reclamation is also converting their construction survey at Auburn Dam to trilateration.

In total, 94 persons attended the courses, representing 21 districts and divisions of the Corps of Engineers, the Bureau of Reclamation, the Tennessee Valley Authority, four private concerns, and one university.

The work performed under this task, although primarily directed towards the training of district survey personnel in the techniques of monitoring movements, has also been directed toward providing techniques of the highest order of accuracy. An analysis has been made of the three sets of measurements taken at Oahe Dam. This analysis, discussing both technique and results is given in Appendix D. The results shown here appear as good as, or perhaps better than, those that have been obtained anywhere else. Therefore, the Corps of Engineers, given proper instrumentation, has added a high precision survey capability second to none to its methods of periodic inspection and continuing evaluation of completed civil works structures.

Appendix A. Report

TRILATERATION MEASUREMENTS AT GREEN PETER DAM, PORTLAND DISTRICT

Prepared by

KENNETH D. ROBERTSON

December 1975

U.S. Army Engineer Topographic Laboroatories
Fort Belvoir, Virginia

TRILATERATION MEASUREMENTS AT
GREEN PETER DAM, PORTLAND
DISTRICT

INTRODUCTION

A series of precise length measurements was made at Green Peter Dam near Sweet Home, Oregon on 29 and 30 September and 1 October 1975 by personnel from the Portland District and from the Engineer Topographic Laboratories, Fort Belvoir, Virginia. The purpose of the measurements was to illustrate a method for monitoring movements in dams and to provide a foundation for a later course to be given on precise measurements with distance measuring equipment (DME).

Two sites with pedestals for mounting the DME had been prepared; one upstream, designated GEO, and one downstream, designated HAUL. A monument, designated CAL (Fig 1), was also set near the end of the dam to serve as a stable reference point. Two other points, FLAG and LEDGE, were at the other end of the dam.

MEASUREMENTS

Measurements were made with a Geodolite Model 3G from GEO, HAUL, and CAL to alignment markers on the dam and to the other control monuments. A typical data sheet, shown in Fig 2, represents a single measurement. The data on each sheet has been reduced in the following manner. The mean of the five fine readings was determined first (1). Next, the reflector and

offset correction was applied. The reflector constants for the four reflectors used at Green Peter were:

#100	1.577
100-2	1.580
100-6	1.578
40I	1.478

In Fig 2, the mean of the two offset values is 1.584 (2) while the reflex constant of 40I (3) is 1.478. The instrument, at the time of the measurement, was reading 1.584 - 1.478 = 0.106 feet too long. This value was then subtracted from the mean of the five fine readings to obtain 8.575 - 0.106 =8.470 which is the corrected fine reading (4). The coarse readings were then applied and the raw slope distance was determined to be 4368.470 feet (5). The raw slope distance, D', was then reduced to the spheroid using equation 1 in the appendix. This observed chord distance on the Clark 1866 spheroid is listed as D^{obs}(6). Finally, the temperature and pressure corrections were applied to obtain the corrected chord spheroid distance D^{corr} (7) using equation 2 in the appendix. The temperature and pressure corrections were only applied to measurements made between control monuments and to the measurements made from CAL to the alignment markers on the dam. Table 1 is a listing of the measurements at Green Peter. Those measurements which have had temperature and pressure corrections applied are listed with an asterisk following the D^{corr} value. Nine measurements were made from GEO to CAL on 29 September with a mean value of 4367.850 feet and two measurements of the same distance were made from CAL on 1 October with a mean value of 4367.862 feet. The mean of these two values, <u>4367.856</u> was taken to

be the true value of the spheroid distance between GEO and CAL. In a similar manner, the following distances were obtained.

GEO-CAL	4,367.856 feet
GEO-HAUL	11,068.553 feet
HAUL-CAL	6,721.786 feet
HAUL-FLAG	6,678.774 feet
HAUL-LEDGE	6,749.815 feet
CAL-FLAG	1,595.514 feet
CAL-LEDGE	1,644.028 feet

The values of the corrected lengths from GEO and HAUL to the alignment markers on the dam were obtained using the distances to CAL as a reference. Referring to Table 1, we have the following values listed for D^{obs} for measurements from GEO.

STA	MEAS#	D^{obs}	CORR	D^{corr}
CAL	5	4367.798	1.00001328	4367.856
27B	6	4649.047	(1.00001311)	4649.108
26A	7	4646.262	(1.00001294)	4646.322
27A	8	4647.452	(1.00001276)	4647.511
CAL	9	4367.801	1.00001259	4367.856

Because a value of 4367.856 has been accepted as the true length from GEO to CAL, the D^{obs} for measurement #5 must be multiplied by an atmospheric correction of 1.00001328. Similarly for measurement #9, a correction of 1.00001259 is required. Assuming the atmospheric change to be linear with time between measurements #5 and #9, a correction factor is obtained for the measurements made in between. These are listed in parenthesis.

The correction factors are applied to obtain the D^{corr} listed in the last column. Values obtained in this manner are listed in Table 1 without an asterisk. The D^{corr} lengths were then used to obtain the positions of the control and alignment monuments.

POSITIONS

In order to approximate the coordinate system already in use at the dam, a position was established for station GEO from the positions of alignment markers 2, 5, 20, and 23, furnished by the Portland District, and from lengths from GEO to those markers. This gave a mean position for GEO of

(All positions are given in feet)*

68725.430
95599.889

The position of CAL was calculated next, using the positions of GEO and alignment markers 2 and 5 and the lengths from these positions. CAL was determined to be

65950.317
92226.921

These two positions establish a coordinate system for the rest of the measurements at Green Peter which is compatible with the system presently in use. At this point, the positions of alignment markers 2, 5, 7, 10, and 11 were redetermined from measurements made from GEO and CAL. Then using CAL together with each of these markers in turn, a mean position

*This entry was not in original text.

of HAUL was determined to be

61829.424
86916.493.

From CAL and HAUL, FLAG was determined as

64560.859
93011.186.

The positions of FLAG, GEO, CAL, and HAUL are the control for the positions or alignment of the markers along the dam. Twelve of the alignment markers were observed from two or more of the control monuments. Twenty-two other markers were observed only from Station GEO. In order to determine the positions of these twenty-two markers, the lengths from FLAG were used. These lengths were taken from differences of position furnished by the Portland District. Positions of certain of the alignment markers were also obtained by measurements from GEO and CAL (the twelve mentioned previously). Two sets of lengths were thus obtained for distances from FLAG to these twelve markers. It was then determined that the measured distances differed from those obtained from the previous data by a scale factor. When the calculated values are multiplied by 0.999945, they agree remarkable well with the measured values. Thus, for the listed distances from Station FLAG this factor has been applied to bring all lengths to the same scale.

RESULTS

Two lengths are necessary to fix the position of an unknown station. If

three lengths are used, three positions of the station may be calculated and if four lengths are used, six positions may be calculated. Using the positions of FLAG (F), GEO (G), CAL (C), and HAUL (H), and the lengths from these stations to alignment markers on the dam, the positions of each marker have been obtained and are given in Table 2. For example, six positions are given for alignment marker #10. From FLAG and GEO, a position of

65071.078
92631.944

is obtained.

From FLAG and CAL, the position is

65071.082
92631.948.

The final position, obtained from measurements from CAL and HAUL is

65071.079
92631.942.

The positions of other alignment markers are given in a similar manner in Table 2. Finally in Table 3, alignment of the markers is given based on several sets of end points. The end points are given at the head of the column.

CONCLUSIONS

If agreement between data taken from different control stations is used as a criteria, then the sensitivity and accuracy of the measurements appears in almost every case to be less than 0.01 foot. The second set

of data may be taken without measurements of temperature and pressure and a comparison of the results with the positions given here will provide a better estimate of overall accuracy. The results thus far obtained, however, look excellent.

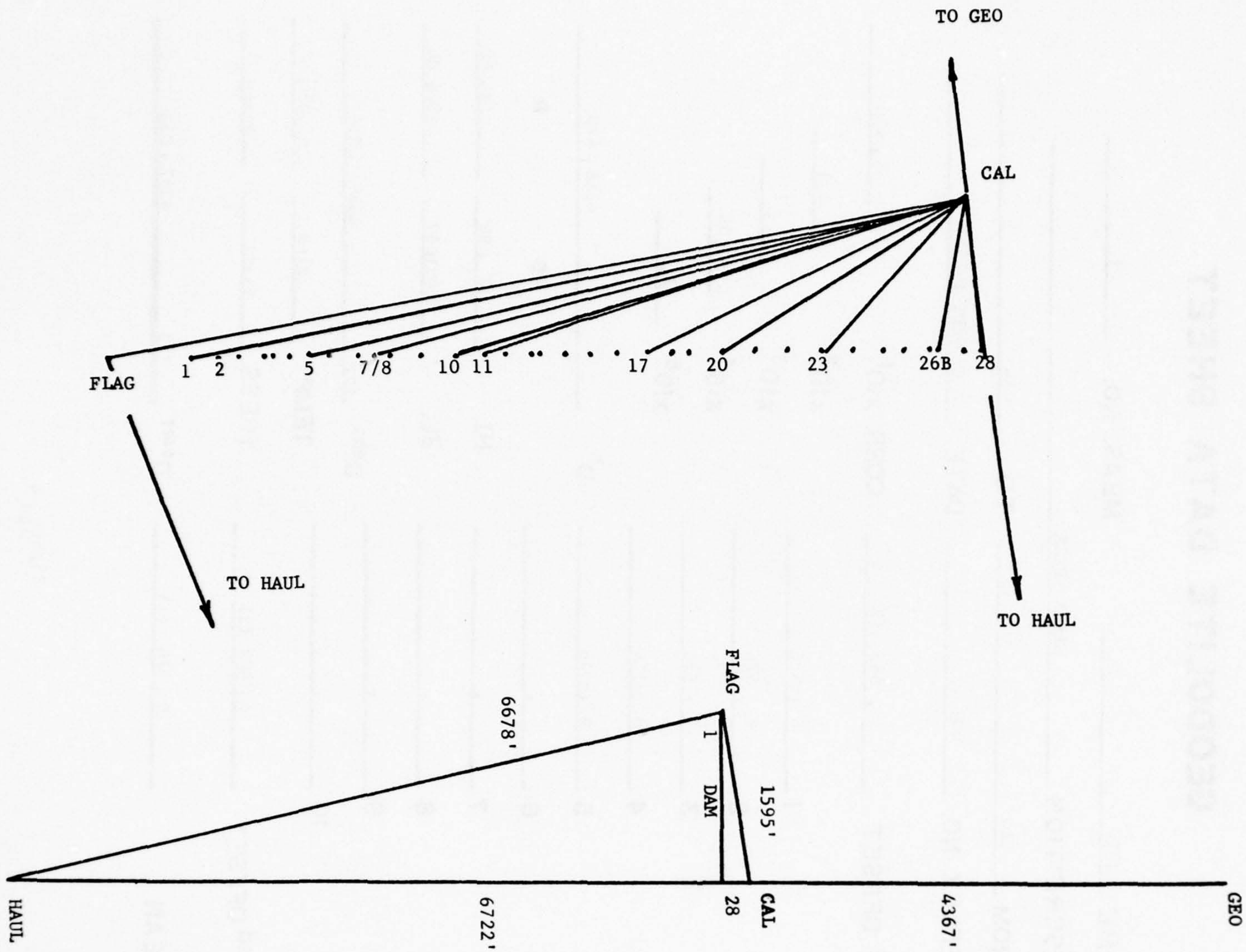


Figure 1. Green Peter.

GEODOLITE DATA SHEET

TIME 1720 MEAS. NO. 9

DESCRIPTION GREEN PETER

FROM GEO TO CAL

REFLEX NO. 401 (3) DATE 29 SEPT 1975

1^{st} OFFSET	1 , 585 (2)	CORR. $x10^1$	(4) 8 , 470
		$x10^2$	6 , 8
1	8 , 576	$x10^3$	3 , 7
2	8 , 576	$x10^4$	4 , 36
3	8 , 576	$x10^5$	0 , 4
4	8 , 576		
5	8 , 576	D^I	(5) 4368 , 470
6	,		G / R
7	,	H.I.	0 , 96 / 3 , 40
8	,	EL.	1091 , 02 / 1026 , 08
9	,	D^{obs}	(6) 4367 , 801
10	,	TEMP.	21 , 8 / 23 , 0
2^{nd} OFFSET	1 , 583 (2)	PRESS.	28 , 83 / 28 , 89
MEAN	8 , 576 (1)	D^{corr}	(7) 4367 , 854

Figure 2.

EQUATION #1 SPHEROID REDUCTION

$$D^{obs}\ (\text{spheroid}) = R \sqrt{\frac{\left[D' - (e_2 - e_1)\right]\left[D' + (e_2 - e_1)\right]}{(R + e_2)\ (R + e_1)}}.$$

R = Earth Radius = 20924400' for Green Peter
D' = Observed Slope Distance
e_1 = Elevation + H.I. of the Instrument
e_2 = Elevation + H.I. of the Reflector

EQUATION #2 REFRACTIVE INDEX CORR.

$$D^{corr} = \frac{1.00027975\ D^{obs}}{1 + \frac{0.002741295\ P}{273.2 + T}}$$

D^{obs} = Observed Distance Reduced to the Spheroid
P = Mean Pressure of Line (Inches of Hg)
T = Mean Temperature of Line (^{o}C)

TABLE 1

MEASUREMENTS AT GREEN PETER DAM

(A) FROM GEO TO

STATION	MEAS. #	D^{obs} (ft)	D^{corr} (ft)
CAL	1	4367.801	4367.855*
HAUL	2	11068.397	11068.560*
CAL	3	4367.794	4367.850*
HAUL	4	11068.392	11068.557*
CAL	5	4367.798	4367.854*
27B	6	4649.047	4649.108
26A	7	4646.262	4646.322
27A	8	4647.452	4647.511
CAL	9	4367.801	4367.854*
25	10	4645.964	4646.023
24	11	4645.953	4646.013
23	12	4646.707	4646.767
22	13	4648.298	4648.359
21	14	4650.581	4650.642
CAL	15	4367.798	4367.844*
20	16	4653.694	4653.755
19	17	4657.622	4657.682
18	18	4660.045	4660.104
17	19	4663.773	4663.831
16	20	4668.846	4668.903
15	21	4674.955	4675.011
CAL	22	4367.805	4367.848*
14B	23	4678.975	4679.029
14A	24	4685.165	4685.219
12B	25	4686.463	4686.516
12A	26	4693.307	4693.359
11	27	4698.341	4698.393
10	28	4707.707	4707.758
9	29	4717.754	4717.805
8	30	4728.531	4728.581
CAL	31	4367.810	4367.844*
7/8	32	4733.799	4733.848
7	33	4742.859	4742.907
6	34	4759.271	4759.319
5	35	4773.790	4773.837
4B	36	4782.772	4782.818
4A	37	4794.481	4794.527
3B	38	4797.850	4797.895
CAL	39	4367.816	4367.850*
3A	40	4815.073	4815.117
2	41	4827.376	4827.421
CAL	42	4367.815	4367.849*

MEASUREMENTS AT GREEN PETER DAM (continued)

(B) FROM CAL TO

STATION	MEAS. #	D^{obs} (ft)	D^{corr} (ft)
GEO	74	4367.847	4367.861*
HAUL	75	6721.746	6721.791*
HAUL	76	6721.747	6721.795*
GEO	77	4367.847	4367.864*
FLAG	78	1595.507	1595.514*
FLAG	79	1595.506	1595.513*
LEDGE	80	1644.021	1644.028*
2	81	1392.593	1392.599*
1	82	1445.821	1445.828*
5	83	1236.424	1236.430*
7/8	84	1110.178	1110.184*
10	85	968.035	968.040*
11	86	910.480	910.485*
23	87	380.464	380.466*
17	88	638.997	639.000*
20	89	518.551	518.553*
28	90	283.866	283.868*
26B	91	285.797	285.800*
CUL	92	266.341	266.343*
CUL	92	366.707	366.710*
CUL	92	466.914	466.918*

(C) FROM HAUL TO

STATION	MEAS. #	D^{obs} (ft)	D^{corr} (ft)
CAL	43	6721.706	6721.793*
GEO	44	11068.396	11068.549*
FLAG	45	6678.683	6678.774*
CAL	46	6721.687	6721.781*
GEO	47	11068.390	11068.548*
FLAG	48	6678.679	6678.774*
CAL	49	6721.684	6721.785*
LEDGE	50	6749.713	6749.815*
1	51	6651.675	6651.783
2	52	6642.843	6642.955
CAL	53	6721.669	6721.775*
5	54	6619.405	6619.521
7/8	55	6603.080	6603.196
10	56	6570.630	6570.745
14B	57	6530.861	6530.976
11	58	6558.285	6558.401

MEASUREMENTS AT GREEN PETER DAM (continued)

(C) FROM HAUL TO (continued)

STATION	MEAS. #	D^{obs} (ft)	D^{corr} (ft)
CAL	59	6721.667	6721.778*
17	60	6506.083	6506.201
20	61	6485.891	6486.011
23	62	6463.973	6464.095
26B	63	6444.939	6445.063
28	64	6438.540	6438.667
CAL	65	6721.651	6721.770*
CAL	66	6721.651	6721.772*
15 TOE	67		
CAL	68	6721.652	6721.776*
15 TOE	69		
CAL	70	6721.655	6721.782*
CAL	72	6721.644	6721.773*

MEASUREMENTS AT GREEN PETER DAM (continued)

(D) FLAG TO

STATION	LENGTH
1	150.492
2	204.058
3A	239.029
3B	289.072
4A	299.030
4B	334.032
5	361.366
6	406.502
7	459.005
7/8	488.772
8	516.456
9	576.018
10	635.727
11	695.845
12A	730.343
12B	780.335
14A	790.278
14B	840.173
15	875.064
16	933.054
17	987.411
18	1032.319
19	1064.683
20	1125.298
21	1185.556
22	1244.502
23	1304.472
24	1364.467
25	1424.363
26A	1459.357
26B	1509.236
27A	1519.230
27B	1568.550
28	1599.470

(Computed with scale factor X.999945)

TABLE 2. ALIGNMENT MARKER POSITIONS, GREEN PETER DAM

GREEN PETER SEP 75

1	64683		F - G	92924	
	*(84	002)	F - C		(678)*
		971	F - H		636
			G - C		
			G - H		
		977	C - H		633
2	64727	785	F - G	92893	817
	*	(790)	F - C		(824)*
		784	F - H		814
		786	G - C		816
		789	G - H		811
		784	C - H		813
3A	64756	392	F - G	92873	703
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

*Values in parenthesis indicate solutions obtained with poor geometry (see figure 1).

GREEN PETER SEP 75

3B	64797	331	F - G	92844	923
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

4A	64805	475	F - G	92839	193
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

4B	64834	111	F - G	92819	064
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

GREEN PETER SEP 75

5	64856	471	F - G	92803	342
		(475)	F - C		(348)
		473	F - H		345
		471	G - C		342
		466	G - H		349
		473	C - H		345

6	64893	390	F - G	92777	375
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

7	64936	339	F - G	92747	178
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

GREEN PETER SEP 75

7/8	64960	683	F - G	92730	047
		(689)	F - C		(056)
		683	F - H		048
		684	G - C		045
		682	G - H		048
		684	C - H		047

8	64981	506	F - G	92711	548
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

9	65026	261	F - G	92671	778
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

10	65071	078	F - G	92631	944
		082	F - C		948
		078	F - H		943
		079	G - C		943
		080	G - H		942
		079	C - H		942
11	65116	174	F - G	92591	871
		174	F - C		870
		174	F - H		870
		174	G - C		871
		178	G - H		867
		174	C - H		870
12A	65142	043	F - G	92568	890
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

12B	65179	514	F - G	92535	593
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

14A	65186	964	F - G	92528	971
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

14B	65224	344	F - G	92495	746
			F - C		
		349	F - H		752
			G - C		
		(325)	G - H		(767)
			C - H		

GREEN PETER SEP 75

15	65250	479	F - G	92472	519
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

16	65293	909	F - G	92433	927
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

17	65334	584	F - G	92397	783
		584	F - C		784
		582	F - H		781
		584	G - C		783
			G - H		
		583	C - H		780

18	65368	234	F - G	92367	892
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

19	65392	468	F - G	92346	373
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

20	65437	847	F - G	92306	071
		839	F - C		060
		851	F - H		075
		841	G - C		077
		(828)	G - H		(090)
		842	C - H		031

GREEN PETER SEP 75

21	65482	948	F - G	92266	005
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

22	65527	058	F - G	92226	811
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

23	65571	953	F - G	92186	968
		955	F - C		969
		958	F - H		973
		955	G - C		967
		(913)	G - H		(7 005)
		954	C - H		976

GREEN PETER SEP 75

24	92147	063	F - G	65616	824
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

25	65661	624	F - G	92107	236
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

26A	65687	839	F - G	92084	018
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

26B	65725		F - G	92050	
		167	F - C		884
		170	F - H		887
			G - C		
			G - H		
		(156)	C - H		(897)

27A	65732	646	F - G	92044	245
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

27B	65769	530	F - G	92011	455
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

GREEN PETER SEP 75

28	65792		F - G	91990		
		635	F - C			876
		636	F - H			878
			G - C			
			G - H			
	(760	790)	C - H		(92015	590)

			F - G		
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

			F - G		
			F - C		
			F - H		
			G - C		
			G - H		
			C - H		

TABLE 3

GREEN PETER ALIGNMENT

STATION	FLAG 7/8	7/8 28	FLAG 28	FLAG CAL
1	.015		11.881	-14.857
2	.003		16.093	-20.162
3A	.006		18.854	-23.614
3B	.011		22.805	-28.554
4A	.009		23.587	-29.541
4B	.014		26.352	-32.995
5	.017		28.511	-35.693
6	.009		32.061	-40.161
7	.011		36.204	-45.347
7/8	.000	.000	38.540	-48.300
8		.001	37.577	-54.174
9		-.003	35.499	-66.809
10		-.014	33.411	-79.469
11		-.020	31.317	-92.200
12A		-.017	30.121	-99.497
12B		-.021	28.381	-110.076
14A		-.023	28.034	-112.180
14B		-.029	26.296	-122.736
15		-.038	25.076	-130.121
16		-.042	23.060	-142.381
17		-.048	21.170	-153.865
18		-.042	19.617	-163.354
19		-.033	18.504	-170.182
20		-.021	16.414	-182.973
21		-.017	14.329	-195.676
22		-.019	12.283	-208.146
23		+.018	10.242	-220.772
24		-.014	8.130	-233.471
25		-.031	6.037	-246.133
26A		+.023	4.879	-253.467
26B		+.049	3.176	-263.971
27A		+.051	2.832	-266.079
27B		+.037	1.108	-276.504
28		.000	.000	-283.067

+ upstream

- downstream

APPENDIX B. REPORT

TRILATERATION MEASUREMENTS AT KEYSTONE DAM
TULSA DISTRICT

Prepared by

KENNETH D. ROBERTSON

August 1976

U.S. Army Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060

INTRODUCTION

A series of precise length measurements was made at Keystone Dam near Tulsa, Oklahoma on 17 and 18 November 1975 by personnel from the Tulsa District and from the Engineer Topographic Laboratories, Fort Belvoir, Virginia. The purpose of the measurements was to illustrate a technique for monitoring movements in dams and to provide a basis for a course in precise measurements to be given 18-22 October in Tulsa.

Three sites with pedestals for mounting the distance measuring equipment (DME) had been prepared by district personnel. These were designated CM-1, and CM - 2, and CM-4 and are shown in figure 1. A further site, designated CM-3, was set on an overlook near one end of the dam to serve as a stable reference point. Finally, five markers SM-1, thru SM-5 were installed in a line along the embankment portion of the dam near the crest.

Measurements

Measurements were made with a Geodolite Model 3G from CM-1, CM-2 and CM-4 to each of the other control monuments and to the markers on the dam. A typical data sheet shown in Figure 2 represents a single measurement. The data on each sheet has been reduced in the following manner. The mean of the five readings was determined first (1). Next the reflector offset correction was applied. The mean of the two offset values (2) was 0.004 short of the reflex constant (3). Thus 0.004 was added to the mean of the five fine readings and recorded as corr x 10 (4). Then the coarse readings were added to give an instrument corrected slope distance D^{I}.(5). Next the elevations of the instrument and reflector were applied using the equation at the top of pg. 45 in the inclosed yellow manual.* This is the observed spheroid chord distance D obs (6). Finally temperature and pressure corrections were applied to obtain the corrected spheroid chord distance D corr (7). The temperature and pressure were only taken for the lines between control monuments.

Table 1A is a listing of measurements taken from CM-1 with the data reduced in the manner detailed above. Lines which have had temperature and pressure corrections applied are marked with an asterisk. Corrected values are also given for the lines to the SM series of markers. These values were obtained differently as explained later in the report.

Table 1B is a similar listing of measurements from monument CM-2 and table 1C is a listing of lengths from CM-4.

The Control Figure

The longest line in the control figure is CM-2 to CM-4 and this line was picked as a basis for a coordinate system. This also places all of the other monuments in the first quadrant with positive values of X and Y.

*Kenneth D. Robertson, The Use and Calibration of Distance Measuring Equipment for Precise Mensuration of Dams, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-0048, March 1976, AD-A023 759.

Control monument CM-2 was arbitrarily assigned a position of X = 1000.000 and Y = 1000.000. CM-4 was also assigned a Y coordinate of Y-1000.000 and X coordinate which would give a distance between CM-2 and CM-4 of 5946.540 feet. This is the mean of the four corrected distances as measured with the Geodolite thus

(All positions are given in feet)*

CM-2	X=1000.000
	Y=1000.000
CM4	X=6946.540
	Y=1000.000

In addition the mean corrected length from CM-2 to CM-3 is 5860.851 and from CM-4 to CM-3 is 5238.821. These lengths together with the positions of CM-2 and CM-4 give a position for CM-3 of X=4553.803
Y=5660.478

The equation at the bottom of pg 47 in the yellow manual** was used for this calculation. Finally, in a similar manner, the position of CM-1 was determined to be

CM-1	X=5519.412
	Y=1616.418

Atmospheric Corrections

No measurements of temperature and pressure were taken for the markers on the dam. The refractive index corrections to the observed distances were made instead through the use of comparisons with a reference line.

Table 2 shows a section of Table 1A, measurements 7 through 15. From measurements of the control figure it has been determined the true distance from CM-1 to CM-3 is 4158.715 feet. When measurement 7 was made the instrument gave a length of 4158.697. The difference between the two values was due to the refractive index. Dividing the true distance by the observed distance gave a refractive index correction of 1.00000433. Sometime later when measurement 9 was made the correction had changed to 1.00000481. Assuming a linear change, the refraction correction for the atmosphere at the time of measurement 8 would have been 1.00000457. Applying this to the observed distance for measurement 8, a refractive index corrected value of 3525.439 was obtained for the length from CM-1 to SM-1. This technique has been used to correct all lengths to the SM series of monuments.

Dam Positions

Table 3 was derived from the corrected lengths of table 2. The lengths of table 3 together with the positions of CM-1, CM-2, and CM-4 yield the positions of Table 4 for the SM series of monuments. Once again the equation at the bottom of pg 47 in the yellow manual was used.**

Finally an alignment calculation was made of SM-2, SM-3 and SM-4 using monuments SM-1 and SM-5 as endpoints. The departures of each marker from a line between the end points is given in table 5.

*This entry was not in original text.

**Kenneth D. Robertson, The Use and Calibration of Distance Measuring Equipment for Precise Mensuration of Dams, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., ETL-0048, March 1976, AD-A023 759.

Conclusions

A compariso· of positions as determined from two sets of lines as given in table 4 shows agreement of about 2 millimeters (.006') in both X and Y. This approaches 1 part per million of the longer distances measured.

KENNETH D. ROBERTSON
Research Physicist
Research Institute

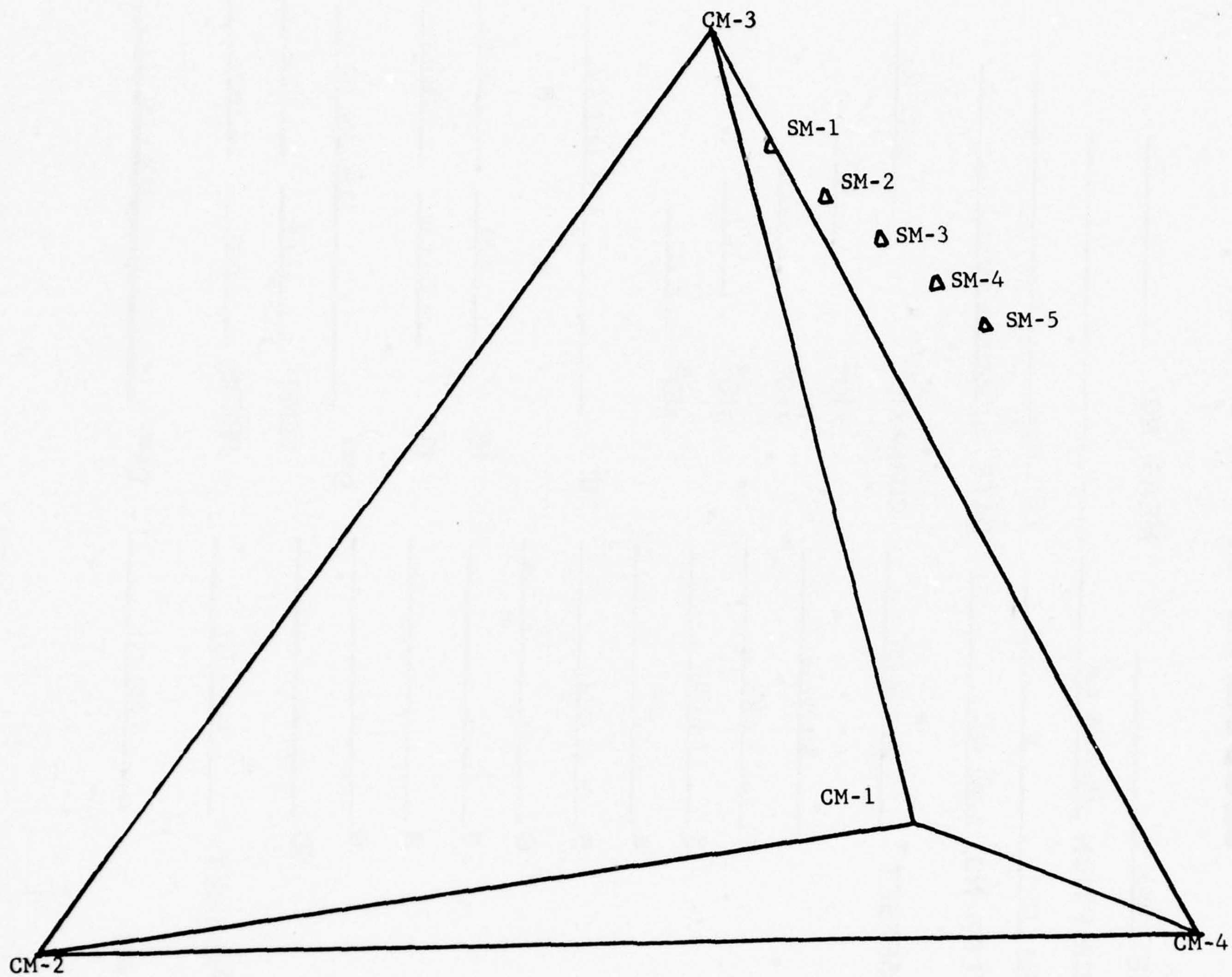


Figure 1. Keystone Dam

GEODOLITE DATA SHEET

TIME 1045 MEAS. NO. 3

DESCRIPTION KEYSTONE DAM

FROM CM-1 TO CM-4

REFLEX NO. 1.568 (3) DATE 17 NOVEMBER 1975

1st OFFSET	1, 564 (2)	CORR. x10¹	4, 372 (4)	
		x10²	5 4	
1	4, 367	x10³	5, 6	
2	4, 368	x10⁴	1, 6	
3	4, 368	x10⁵	0, 1	
4	4 368			
5	4, 368	D¹	1554, 372 (5)	
6			G	R
7		H.I.	0, 93	0, 30
8		EL.	691, 46	714, 61
9				
10		Dobs	1554, 157 (6)	
		TEMP.	17, 8	19, 2
2nd OFFSET	1, 564 (2)	PRESS.	29, 40	29, 38
MEAN	4, 368 (1)	Dcorr	1554, 162 (7)	

Figure 2.

TABLE 1A
MEASUREMENTS FROM CM-1

MEAS No	STATION	D obs	D corr
1	CM-3	4158.701	4158.716*
2	CM-2	4561.101	4561.114*
3	CM-4	1554.157	1554.162*
4	CM-4	1554.156	1554.161*
5	CM-3	4158.697	4158.713*
6	CM-2	4561.098	4561.112*
7	CM-3	4158.697	4158.715*
8	SM-1	3525.423	3525.439
9	CM-3	4158.695	4158.712*
10	SM-2	3238.191	3238.207
11	SM-3	2973.361	2973.375
12	CM-3	4158.695	4158.713*
13	SM-4	2737.122	2737.135
14	SM-5	2533.232	2533.243
15	CM-3	4158.697	4158.716*

TABLE 1B
MEASUREMENTS FROM CM-2

MEAS No	STATION	D obs	D corr
16	CM-1	4561.094	4561.125*
17	CM-4	5946.504	5946.541*
18	CM-3	5860.807	5860.854*
19	CM-1	4561.095	4561.128*
20	CM-4	5946.502	5946.541*
21	CM-3	5860.805	5860.853*
22	CM-3	5860.802	5860.849*
23	SM-1	5554.184	5554.231
24	CM-3	5860.801	5860.848*
25	SM-2	5593.705	5593.753
26	SM-3	5657.996	5658.044
27	CM-3	5860.800	5860.849*
28	SM-4	5745.855	5745.904
29	SM-5	5858.104	5858.154
30	CM-3	5860.801	5860.850*

TABLE 1C
MEASUREMENTS FROM CM-4

MEAS No	STATION	D obs	D corr
31	CM-3	5238.811	5238.818*
32	CM-1	1554.171	1554.172*
33	CM-2	5946.536	5946.541*
34	CM-2	5946.534	5946.539*
35	CM-1	1554.170	1554.170*
36	CM-3	5238.809	5238.817*
37	CM-3	5238.804	5238.820*
38	SM-1	4602.290	4602.305
39	CM-3	5238.803	5238.825*
40	SM-2	4254.112	4254.128
41	SM-3	3913.847	3913.862
42	CM-3	5238.799	5238.821*
43	SM-4	3583.723	3583.738
44	SM-5	3260.423	3260.437
45	CM-3	5238.798	5238.823*

TABLE 2
REFRACTIVE INDEX CORRECTIONS
FROM CM-1
TRUE LENGTH CM-1 TO CM-3 = 4158.715

MEAS No	STATION	D obs	R.I. CORR	D corr
7	CM-3	4158.697	1.00000433	
8	SM-1	3525.423	(1.00000457)	3525.439
9	CM-3	4158.695	1.00000481	
10	SM-2	3238.191	(1.00000481)	3238.207
11	SM-3	2973.361	(1.00000481)	2973.375
12	CM-3	4158.695	1.00000481	
13	SM-4	2737.122	(1.00000465)	2737.135
14	SM-5	2533.232	(1.00000449)	2533.243
15	CM-3	4158.697	1.00000433	

TABLE 3

LENGTHS TO DETERMINE
POSITIONS

STATION	CM-1	LENGTHS CM-2	FROM CM-4
SM-1	3525.439	5554.231	4602.305
SM-2	3238.207	5593.753	4254.128
SM-3	2973.375	5658.044	3913.862
SM-4	2737.135	5745.904	3583.738
SM-5	2533.243	5858.154	3260.437

TABLE 4

POSITIONS

	- OBTAINED FROM - CM-1 & CM-2	CM-2 & CM-4
SM-1	X = 4786.196	4786.202
	Y = 5063.767	5063.761
SM-2	X = 5082.519	5082.526
	Y = 4824.017	4824.010
SM-3	X = 5377.042	5377.040
	Y = 4585.383	4585.385
SM-4	X = 5669.407	5669.402
	Y = 4348.440	4348.447
SM-5	X = 5964.982	5964.976
	Y = 4109.168	4109.177

TABLE 5

ALIGNMENT

STATION	DEPARTURE	DISTANCE FROM SM-1
SM-2	-0.168	381.166
SM-2	-0.072	760.230
SM-4	+0.069	1136.554

+ DOWNSTREAM

- UPSTREAM

Appendix C. Course Letter of Acknowledgment

DEPARTMENT OF THE ARMY
UNITED STATES ARMY ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060

ETL-RI

Dear

Your application for the training course, entitled: "Development of High Precision Survey Capability" has been accepted for the week of 20-24 September at Green Peter Dam near Albany, Oregon.

We would like to make the course as practical as possible. It is designed for the field surveyor using or contemplating the use of distance measuring equipment and/or the surveyor with the responsibility for making measurements of dam displacements.

A course outline is inclosed. Note that during the final day, time will be set aside for discussion of specific problems you may have. I hope many of the class will be able to stay for this session to provide an exchange of information and ideas.

The course will be held at Green Peter Dam and at the Swept Wing Motel, 1212 Price Road, Albany, Oregon 97321, Telephone (503) 926-6031. The motel is near the intersection of Interstate Route 5 and Route 20. The class will begin there at 1300 on 20 September 1976.

Information on motel accommodations and reservations may be obtained from:

Mr. Roger Campbell
Survey Section
Portland District, Corps of Engineers
P.O. Box 2946
Portland, Oregon 97208

ETL-RI

The district will not be able to furnish transportation.

A hand calculator with trig function will be useful but not necessary.

I appreciate your interest and look forward to seeing you in September. If you have any questions regarding the course write or call me at (703) 664-6194.

Sincerely yours,

Kenneth D Robertson

KENNETH D. ROBERTSON
Research Physicist
Research Institute

1 Incl
As stated

DEVELOPMENT OF HIGH PRECISION SURVEY
CAPABILITY

Course Outline

Sep 20 - Swept Wing Motel, Albany, Oregon

1300-1700
How Distance Measuring Equipment works - Error sources: how to recognize and avoid them - Calibration techniques.

Sep 21
0800-1200
Atmospheric corrections - Baseline measurement.

1300 - 1700
Ratios - Proper Geometry
Trilateration vs. Triangulation.

Sep 22 - Green Peter Dam
0800-1200
Field measurements - Reflector calibration - Baseline.

1300-1700
Control figure and dam measurements - Ratios.

Sep 23
0800-1200
Calculations and data reduction.

1300-1700
Examination of a dam from beginning to end.

Sep 24
Review of data reduction and use of ratios.

Questions - General discussion of Specific Problems (Please bring yours).

Appendix D.

THE USE OF ATMOSPHERIC MODELS WITH TRILATERATION[1]

US Army Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060

[1] Kenneth D. Robertson, "The Use of Atmospheric Models with Trilateration," Survey Review, vol xxiv, 186, October 1977.

ABSTRACT

In trilateration, when lengths are observed in pairs or groups, it is frequently possible to apply refractive index corrections obtained from an atmospheric model. This paper presents a comparison of results using a model with those obtained from temperature and pressure measurements.

Three series of length measurements have been made at Oahe Dam, a large earth filled structure on the Missouri River in South Dakota, U.S.A. The measurements were made to monitor possible movements of the dam and to provide a test of atmospheric reduction techniques which might improve the precision of the survey and if possible reduce the time and personnel required. The measurements were made during June 1973, October 1973, and May 1974. The approach used was to measure lengths in pairs or groups from a single station within a short period of time. It is believed that lengths measured in this fashion exhibit the following two proper ties:

1. The ratio of the observed lengths of two lines, measured at the same time and from the same station, remains constant.
2. The corrected lengths of two lines measured at the same time and from the same station contain similar scale errors.

Observed lengths are those which have not been corrected for the refractive index of the air. Corrected lengths are those to which refractive index corrections have been applied. "At the same time" was considered to be within a period of sixty minutes although the experience gained at Oahe indicates thirty minutes would have been a better choice.

THE CONTROL FIGURE

It is desired to measure possible movements of marks on the dam relative to stable control positions which are sufficiently remote to be free of the forces acting on the structure. Because of terrain and other factors this is not always possible and it becomes necessary to measure the control figure during each survey to determine the stability of the control monuments.

Figure 1 shows the positions of four of the control monuments at Oahe Dam. Measurements of the dam were made from three of these, PHCMY-A, F1-A, and Snake Butte. The fourth monument, CM-3B, served as a reference. Table 1 lists the observed and corrected distances for the primary triangle for each of the three series of measurements. The lengths, both observed and corrected, have been reduced to chord distances on the Clarke 1866 spheroid. Previous studies (1) have shown the potential advantages of measuring lines in pairs or groups and of computing angles from ratios rather than from line lengths. Thus, in the triangle ABC of Figure 2, if D, E, and F are the ratios of the lengths a, b, and c measured from the three vertices, the COS of angle c is given by

$$(1) \quad \text{COS } C = 1/2 \left(F + \frac{1}{F} - \frac{E}{D} \right)$$

Similar expressions may be derived for the other two angles of the triangle. Using the corrected lengths from Table 1, June 1973, the following ratios and angles are obtained.

$D = 12083.086 / 11125.304 = 1.08609041$

$E = 11125.298 / 13747.433 = 0.80926366$

$F = 13747.421 / 12083.089 = 1.13774061$

$A = 72^{\circ}\ 30'\ 52''.29$

$B = 56^{\circ}\ 57'\ 47''.91$

$C = 50^{\circ}\ 31'\ 19''.80$

When this computation is performed using the other lengths from Table 1 a comparison of angles may be made for the three series of measurements. Table 2 gives the result of the comparison for both observed and corrected distances.

The agreement between the three series for either the corrected ratios or the observed ratios is much better than the agreement between the corrected ratios and the observed ratios for one series of measurements. This is because lines at different elevations travel through air of different refractive indices and no account has been taken of this with the observed ratios. It does, however, bear out the validity of the assumed property of length ratios, namely that the observed ratio remains constant with time. Table 3 gives the elevations of the four control monuments.

The refractive index equation for correcting distance measuring instruments may be written in the form

$$(2)\ Lcorr = \frac{k\ LOBS}{n}$$

Lcorr is the corrected length, LOBS the observed length, k is a constant for the instrument (the refractive index for which the instrument

gives a correct length), and n is the mean refractive index along the line.

If two measurements are made within a short period of time:

$$(3) \quad \frac{\text{Lcorr 1}}{\text{Lcorr 2}} = \frac{\text{k LOBS 1}}{\text{k LOBS 2}} \cdot \frac{n_2}{n_1}$$

The ratio of the corrected lengths is a constant. Thus, if the ratio of observed lengths is a constant it is because the ratio of refractive indices is a constant. Although it may not be possible to use an atmospheric model to determine a true refractive index for either line a model may be used to determine the ratio of the two. That is $\frac{n_2}{n_1} = \frac{n\ MOD_2}{n\ MOD_1}$ although $n_2 \neq n\ MOD_2$ and $n_1 \neq n\ MOD_1$

This was done with the data taken at Oahe dam by assuming that a standard sea level temperature of 20°C and pressure of 29.92 inches of mercury existed at the moment each length was measured. Because the ratio is almost independent of the actual sea level conditions these need not be known.

The instrument used at Oahe Dam was the Geodolite Model 3G built by Spectra Physics. Equation (2) for the Geodolite is written

$$(4) \quad \text{Lcorr} = \frac{1.00027975\ \text{LOBS}}{n}.$$

n, the refractive index of the line, is given by

$$(5) \quad n = 1 + \frac{0.002741295P}{273.2 + T}$$

where P is atmospheric pressure in inches of Hg and T is the temperature in °C. A pressure and temperature model was then used to determine n as a function of the midpoint elevation, h, of each line.

The value of P was determined from a barometric altimetry equation

$$(6)\quad P = 29.92\ (1\text{-}0.0000068754h)^{5.2561}$$

and T was determined from a simple linear lapse rate.

$$(7)\quad T = 20 - 0.0025h$$

Substituting these equivalents for T and P into (5) then provided an equation for n as a function of the elevation, h, of the midpoint of the line. Finally, this value of n was used in (4) together with the observed length to obtain a model length, L_{MOD}.

$$L_{MOD} = \frac{k\ LOBS}{n_{MOD}} \quad \text{and from (3)}$$

$$(8)\quad \frac{Lcorr\ 1}{Lcorr\ 2} = \frac{LMOD\ 1}{LMOD\ 2}$$

Table 4a lists model lengths for the three series of measurements. These have been obtained from the observed lengths of Table 1 and the midpoint elevations of the lines. The model lengths have then been used to determine the angles of the triangle PHCMY-A, Snake Butte, F1-A and are listed in Table 4b. Agreement between these angles and those obtained from ratios of corrected lengths has been improved through the use of the atmospheric model.

The model used at Oahe Dam does well for projects of limited extent where large differences in elevation do not occur. However, in a strict sense the model suffers from two defects which become more important, where longer lines and greater elevation differences are involved. The first of these is the obvious one that temperature gradients do not behave in a predictable way. The second defect is the assumption of an unchanging standard condition at sea level. An example will show the magnitude of these effects for an Oahe Dam ratio.

In the primary triangle, PHCMY-A, Snake Butte, Fl-A the lines from PHCMY-A have the largest difference in elevation. From Table 1, series 1 and Table 3 the lengths and midpoint elevations of the two lines are:

	Observed length	Midpoint el.
PHCMY-A to Fl-A	13747.145 feet	1652 feet
to Snake Butte	12082.811 feet	1829 feet

The model lengths derived from these observed distances depends on the assumed temperature gradient for the model. Table 5 shows the effect of the gradient on the ratio of the model lengths of the two lines.

Table 6 shows the effect of the assumed sea level reference conditions on the same ratio.

The tables show that the temperature gradient is by far the more important of the two effects, but even if the gradient were in error by as large an amount as $5^{o}C/1000$ feet the effect on the ratio would be less than one part per million. The agreement between the three series of measurements bears this out.

While the results from only one triangle have been given here, experience with large numbers of measurements in several locations indicates that with ratios slightly more consistent results are obtained from models than from refractive index measurements and with less effort. The poorest result are those where the corrected lengths are used directly without forming ratios.

MONUMENTS ON THE DAM

A slightly different technique has been used to monitor movement of monuments on the dam. In order to produce measurements in an efficient manner it is not practical to occupy each of the monuments on the dam with the instrument. Instead measurements are made to each monument from at least two of the control monuments. At Oahe Dam F1-A and Snake Butte were used for this purpose. Ten monuments along the crest of the dam were measured from the two control points for each of the three series of measurements. Additional measurements from PHCMY-A have not been included because these were made only during the second and third series.

In order to use an atmospheric model with data of this type a reference monument, CM-3B, was established and made a part of the control network. Positions were assigned to the four control monuments as follows:

F1-A	X = 10000.000 Y = 10000.000
Snake Butte	X = 21125.308 Y = 10000.000
CM-3B	X = 5238.151 Y = 14940.070
PHCMY-A	X = 17494.777 Y = 21524.767

The coordinate system is derived from a PHCMY-A to F1-A length of 13747.434 feet and the mean of corrected angles from the three series of measurements.

The observational procedure for measurements of the dam was to first measure to the reference monument CM-3B, then to several of the dam

monuments and then finally to the reference again.

Table 7 is an example of such a set of measurements. Column (1) consists of lengths to which a model refractive index has been applied. Equation (8) may be rewritten as

$$L_{corr\ 1} = \frac{L_{MOD1} \times L_{corr\ 2}}{L_{MOD\ 2}}$$

The table gives the true length of the line from Snake Butte to CM-3B and a model length. If these values are substituted into the equations the length of the line from Snake Butte to SC 5 may be determined

$$L_{REF} = \frac{13485.183 \times 16637.489}{16637.283} = 13485.350$$

The length L_{REF} to SC 5 has had two atmospheric corrections applied to it. The first was the calculation of L_{MOD}, which took the midpoint elevation of the line into account. The use of a reference line has applied a correction for the actual temperature and pressure at sea level at the time the line was measured. L_{REF} in the table are lengths obtained in this manner and Lcorr are the lengths which have had the measured refractive index applied. One final step needs to be taken to obtain the L_{REF} lengths. This is to allow for changes in the model length of the reference line. This length changed from 16637.283 to 16637.273 during the 75 minute measuring period. The values of L_{REF} for lines to positions on the dam have been determined by assuming a linear change in the length of L_{REF} as a function of time.

The values of L_{REF} and Lcorr have been calculated for ten monuments on the dam from both F1-A and Snake Butte for all three series of monuments. From these lengths and the positions of F1-A and Snake Butte

coordinates have been determined for the 10 monuments and are listed in Table 8. An examination of this table indicates that slightly better repeatability is obtained in the X direction from use of an atmospheric model, with a standard deviation on the order of 0.011 feet compared with .015 feet for the corrected data. In the Y direction the reverse is true with standard deviations of 0.005 and .007 being obtained. The mean line lengths involved were 13400 feet in the X direction and 9500 feet in Y.

CONCLUSIONS

During three trips to Oahe Dam almost 1000 lines were measured to monitor movements of the dam and to develop techniques for reducing the effects of atmospheric refraction. The results presented here, while only a portion of the total, are believed to be typical of the whole. They show that the use of a simple atmospheric model provides results as good as or better than those obtained from temperature and pressure measurements made at the end points of the lines. Further, the region around Oahe Dam is arid and devoid of trees and is subject to rather strong winds. These conditions contribute to good mixing of the air in the lower atmosphere and thus permit unusually accurate temperature measurements to be made. Experience in other areas, particularly calm sheltered ones, indicates an even greater improvement through the use of models. At Oahe Dam it was possible to measure both the control figure and the positions of the monuments on the dam with measurements of temperature and pressure being made on only one line, to provide scale, and only during the first series of measurements.

The techniques developed at Oahe Dam are now being used on several dams with equivalent results, the limiting factor in most cases being the distance measuring instruments available rather than the problems involved with accurate determinations of refractive index.

TABLE 1

OBSERVED & CORRECTED LENGTHS
(feet)

SERIES 1 JUNE 1973

DATE		TIME	OBSERVED	CORRECTED
SNAKE BUTTE	TO PHCMY-A	1100	12082.804	12083.086
6-25	TO F1-A	1107	11125.039	11125.304
F1-A	TO SNAKE BUTTE	0932	11125.069	11125.298
6-26	TO PHCMY-A	1025	13747.140	13747.433
PHCMY-A	TO F1-A	1408	13747.145	13747.421
6-27	TO SNAKE BUTTE	1410	12082.811	12083.089

SERIES 2 OCTOBER 1973

DATE		TIME	OBSERVED	CORRECTED
SNAKE BUTTE	TO PHCMY-A	1000	12083.064	12083.066
10-16	TO F1-A	1035	11125.304	11125.304
F1-A	TO SNAKE BUTTE	0852	11125.264	11125.294
10-17	TO PHCMY-A	0921	13747.397	13747.428
PHCMY-A	TO F1-A	0904	13747.366	13747.430
10-18	TO SNAKE BUTTE	0906	12083.028	12083.096

SERIES 3 MAY 1974

DATE		TIME	OBSERVED	CORRECTED
SNAKE BUTTE	TO PHCMY-A	0916	12082.945	12083.103
5-7	TO F1-A	0858	11125.189	11125.320
F1-A	TO SNAKE BUTTE	1002	11125.230	11125.320
5-6	TO PHCMY-A	1016	13747.340	13747.450
PHCMY-A	TO F1-A	0841	13747.324	13747.444
5-8	TO SNAKE BUTTE	0839	12082.965	12083.091

TABLE 2

ANGLES FROM THREE SERIES OF MEASUREMENTS

ANGLE	SERIES 1	SERIES 2	SERIES 3
	USING CORRECTED RATIOS		
A 72^{o} 30'	52".29	52".33	52".41
B 56^{o} 57'	47".91	47".71	47".76
C 50^{o} 31'	19".80	19".96	19".83
	USING OBSERVED RATIOS		
A 72^{o} 30'	52".61	52".55	52".70
B 56^{o} 57'	47".66	47".55	47".41
C 50^{o} 31'	19".73	19".90	19".89

TABLE 3

MONUMENT ELEVATIONS
(feet)

SNAKE BUTTE	1922
F1-A	1568
PHCMY-A	1736
CM-3B	1797
MARKERS ON THE DAM	1959-1664

Elevations are given to the nearest foot for the purpose of computing an atmospheric model.

TABLE 4

MODEL LENGTHS AND ANGLES

(a) MODEL LENGTHS

		SERIES 1	SERIES 2	SERIES 3
SNAKE BUTTE	TO PHCMY-A	12082.971	12083.231	12083.112
	TO F1-A	11125.186	11125.451	11125.336
F1-A	TO SNAKE BUTTE	11125.216	11125.411	11125.377
	TO PHCMY-A	13747.312	13747.569	13747.512
PHCMY-A	TO F1-A	13747.317	13747.538	13747.496
	TO SNAKE BUTTE	12082.978	12083.195	12083.132

(b) ANGLES FROM MODEL RATIOS

ANGLE	SERIES 1	SERIES 2	SERIES 3
A 72° 30'	52.30	52.23	52.39
B 56° 57'	47.92	47.81	47.67
C 50° 31'	19.78	19.96	19.94

ANGLES FROM CORRECTED RATIOS (TABLE 2)

ANGLE	SERIES 1	SERIES 2	SERIES 3
A 72° 30'	52.29	52.33	52.41
B 56° 57'	47.91	47.71	47.76
C 50° 31'	19.80	19.96	19.83

TABLE 5

MODEL RATIO AS A FUNCTION OF TEMPERATURE GRADIENT

GRADIENT $^{o}C/1000'$	RATIO
+5	1.13774 121
+2.5	1.13774 160
0	1.13774 201
-2.5 Oahe Model	1.13774 244
-5.0	1.13774 290
-7.5	1.13774 339
-10.0	1.13774 392

A negative gradient is taken to mean a decrease in temperature with an increase in elevation.

The reference conditions at sea level are 20^{o}C and 29.92 inches mercury.

TABLE 6

MODEL RATIO AS A FUNCTION OF ASSUMED REFERENCE CONDITIONS

REF. TEMP °C	REF.PRESS "Hg	RATIO
20	27.92	1.13774 254
20	28.92	1.13774 250
20 Oahe Model	29.92	1.13774 244
-20	29.92	1.13774 229
40	29.92	1.13774 251
40	27.92	1.13774 261
-20	30.92	1.13774 223

TABLE 7

MEASUREMENTS FROM SNAKE BUTTE 25 JUNE 1973

TRUE LENGTH OF REFERENCE LINE = 16637.489

TIME	TO MONUMENT	(1) L MOD	(2) L REF	(3) L CORR
1250	CM 3B	16637.283	16637.489	16637.452
1300	SC 5	13485.183	13485.351	13485.324
1315	SC 4	13766.256	13766.429	13766.408
1342	SC 3	13931.551	13931.729	13931.704
1400	SC 2	14074.693	14074.875	14074.848
1405	CM 3B	16637.273	16637.489	16637.452

TABLE 8

POSITIONS FROM SNAKE BUTTE & F1-A

			SERIES 1	SERIES 2	SERIES 3
SC 1	REF.	X	8507.705	.703	.706
		Y	17186.173	.174	.176
	CORR.	X	8507.735	.748	.723
		Y	17186.167	.180	.181
SC 2	REF.	X	9414.900	.914	.933
		Y	17808.231	.241	.240
	CORR.	X	9414.937	.959	.946
		Y	17808.237	.247	.244
SC 3	REF.	X	9744.197	.207	.262
		Y	18035.135	.114	.120
	CORR.	X	9744.222	.251	.275
		Y	18035.127	.119	.126
SC 4	REF.	X	10156.233	.233	.219
		Y	18318.292	.269	.272
	CORR.	X	10156.251	.267	.235
		Y	18318.280	.272	.279
SC 5	REF.	X	10980.669	.650	.661
		Y	18884.876	.863	.869
	CORR.	X	10980.694	.693	.685
		Y	18884.864	.865	.875
SC 6	REF.	X	11804.433	.425	.441
		Y	19450.671	.659	.664
	CORR.	X	11804.463	.471	.464
		Y	19450.664	.655	.667
SC 7	REF.	X	12666.926	.925	.926
		Y	20043.218	.217	.213
	CORR.	X	12666.949	.967	.938
		Y	20043.211	.208	.214
SC 8	REF.	X	13545.943	.944	.945
		Y	20407.095	.097	.083
	CORR.	X	13545.964	.979	.951
		Y	20407.083	.081	.083
SC 9	REF.	X	14192.713	.729	.705
		Y	20675.138	.141	.130
	CORR.	X	14192.729	.755	.713
		Y	20675.125	.119	.129
SC 10	REF.	X	15394.941	.955	.930
		Y	21172.823	.829	.828
	CORR.	X	15394.950	.978	.941
		Y	21172.811	.807	.823

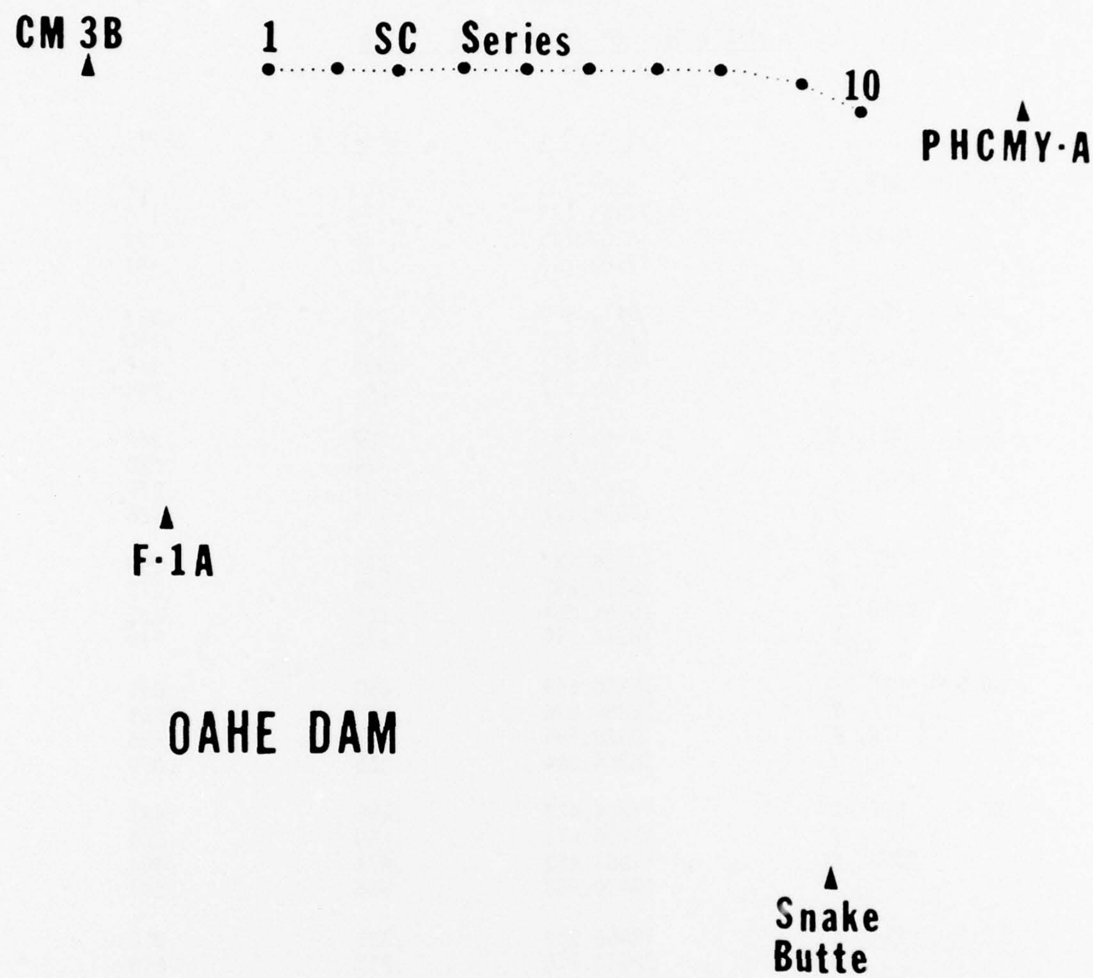
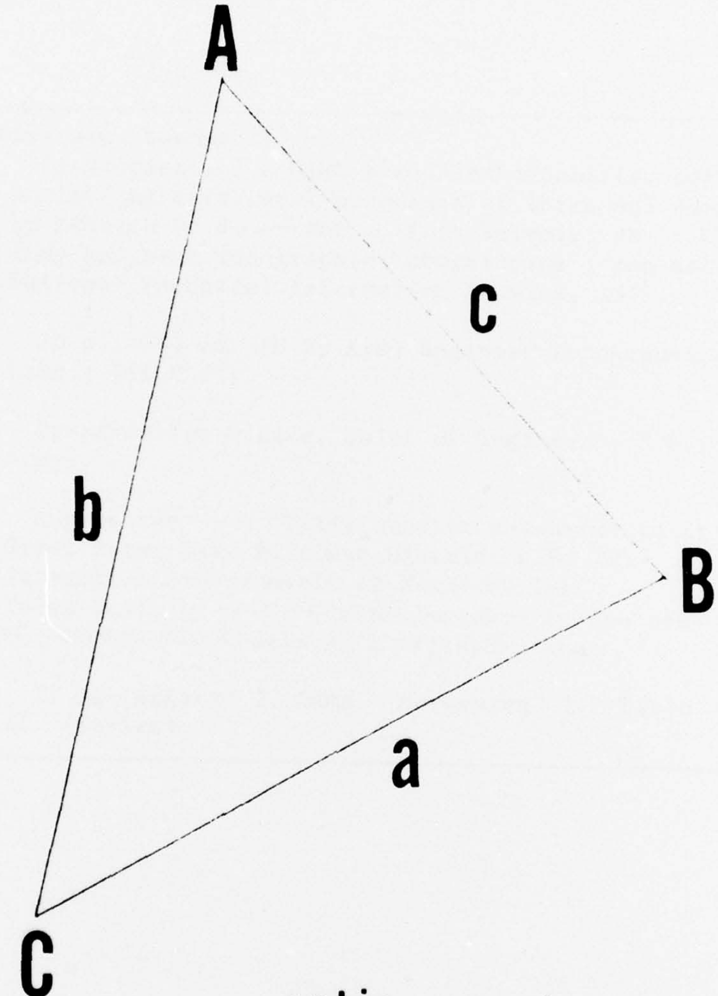


FIGURE 1

OAHE DAM MEASUREMENTS



ratio $D = b/c$

$E = c/a$

$F = a/b$

FIGURE 2

RATIOS

Robertson, Kenneth D.
Development of a high precision capability for monitoring structural movements of locks and dams/ by Kenneth D. Robertson — Fort Belvoir, Va. : U.S. Army Engineer Topographic Laboratories : for sale by National Technical Information Service, 1977.

70 p.; 25½ cm. (U.S. Army Engineer Topographic Labs.; ETL 0121)

Prepared for Office, Chief of Engineers, U.S. Army.

Appendices: – A. Trilateration measurements at Green Peter Dam, Portland District – B. Trilateration measurements at Keystone Dam, Tulsa District – C. Course letter – D. The use of atmospheric models with trilateration.

1. Dam safety 2. Dams - Surveying I. Title II. (Series)